

## TESTING BIMODAL PLANET FORMATION

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Draft version February 2, 2008

### ABSTRACT

We suggest that the observed break in giant-planet frequency as a function of host metallicity at  $Z = 0.02$  may be a reflection of bimodal planet formation. We search for signatures of this bimodality in the distributions of the planet eccentricities, periods, masses, and multiplicity. However, the low-metallicity sample is at present too small to test for any but the most severe differences in these two putative populations.

*Subject headings:* planetary systems – planetary systems: formation – stars: abundances

### 1. TEST OF BIMODALITY

Fischer, Valenti & Marcy (2003) have demonstrated that the frequency of extra-solar giant planets is a strong function of metallicity  $Z$ . Santos, Israelian & Mayor (2004) have confirmed this result and have further shown that there is a sharp break in frequency at  $Z = 0.02$ , which can be represented algebraically by,

$$f = 0.025 + 16(Z - 0.02)\Theta(Z - 0.02), \quad (1)$$

where  $\Theta$  is a step function. See their figure 7. We suggest that the two terms of this equation correspond to two different modes of giant-planet formation, the first being metallicity-independent and the second being strongly dependent on metallicity. For example, in its simplest form, the

disk-instability model of Boss (1995) would not be expected to depend on metallicity. By contrast, the more conventional picture of gas accretion onto rock-ice cores might well be very sensitive to metallicity.

If the two mechanisms generated planets with substantially different distributions in eccentricity, period, or mass, then these should be revealed in the observed distributions of these properties as functions of metallicity. That is, the planets with  $Z < 0.02$  should entirely reflect one distribution, while those with  $Z \geq 0.02$  should predominantly reflect the other.

To test this possibility, we make three plots. In Figures 1, 2, and 3, we show the eccentricities  $e$ , periods  $P$ , and mass functions  $M \sin i$  of the 109 planets cataloged by Santos et al. (2004) versus the metallicities of their 97 host stars. We exclude HD 47536 as its planet's properties are not well established. We take planet properties from The Geneva Extrasolar Planet Search Programmes website<sup>1</sup>.

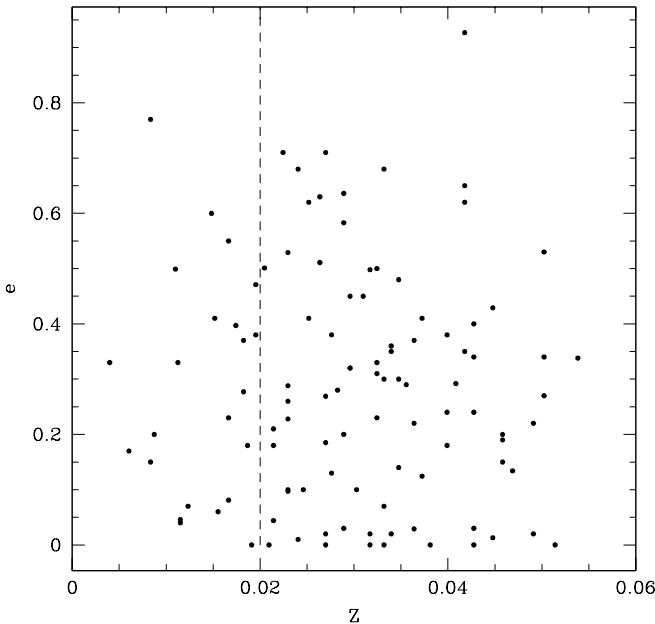


FIG. 1.— Eccentricity  $e$  vs. metallicity  $Z$  for the 109 planets of the 98 stars with metallicities determined by Santos et al. (2004) with the exception of HD 47536b. If the break in the frequency of planets at  $Z = 0.02$  reflects bimodal planet formation, one might expect this to be reflected in a similar break in the eccentricity distribution at this boundary (dashed line). No such break is visible, but the present statistics would be sufficient to reveal only the most glaring differences.

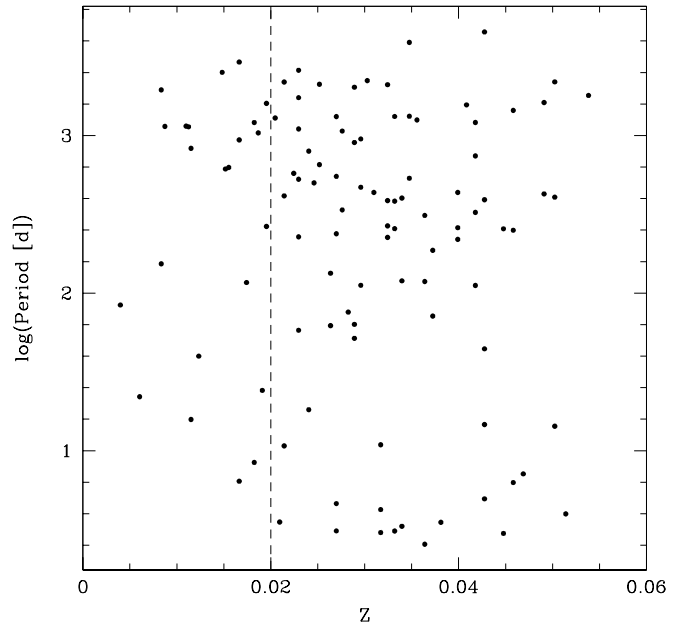


FIG. 2.— Same as Fig. 1, but for period  $P$  vs. metallicity  $Z$ .

No strong pattern emerges from any of these three plots. The low- $Z$  stars show a modest deficit of short-period planets, but a Kolmogorov-Smirnov (KS) test shows a significance of only  $p = 0.17$ . Similarly, the low- $Z$  stars show a modest deficit of high-mass planets, but this is even less significant ( $p = 0.21$ ). However, because only 23 of the 109 planets have metallicities  $Z < 0.02$ , these plots and tests would only be sensitive to the most glaring differences between the two putative populations.

Since there are marginal signals in each of Figures 2 and 3, we have also plotted (but do not show)  $P$  vs.  $M \sin i$ , with different symbols for the planets of stars above and below  $Z = 0.02$ . However, we find no enhanced signal in this plot, nor indeed in similar plots of  $e$  vs.  $P$  and  $e$  vs.  $M \sin i$ .

We can also check whether planetary multiplicity is bimodal in character. Of the 75 planet-bearing stars with  $Z \geq 0.02$ , 9 have more than one planet. If multiplicity were independent of metallicity, we would expect 2.64 of the 22 planet-bearing stars with  $Z < 0.02$  to have multiple planets. In fact, there is only one such metal-poor multiple system. Again, however, no strong significance can be attached to this difference because, based on Poisson statistics, such a shortfall would be expected 26% of the time.

Now that a clear break point has been established in planet frequency at  $Z = 0.02$ , it is critical to establish a larger sample of planets of sub-solar metallicity stars. The relatively low frequency of these planets will make this search difficult, partly because a large number of such stars must be searched and partly because, as a consequence of this, these stars will tend to be farther away and so fainter. Nevertheless, since a comparison of the planet properties of host stars above and below  $Z = 0.02$  is the simplest test for bimodal planet formation, the additional effort required to enhance the low-metallicity

sample would be well justified.

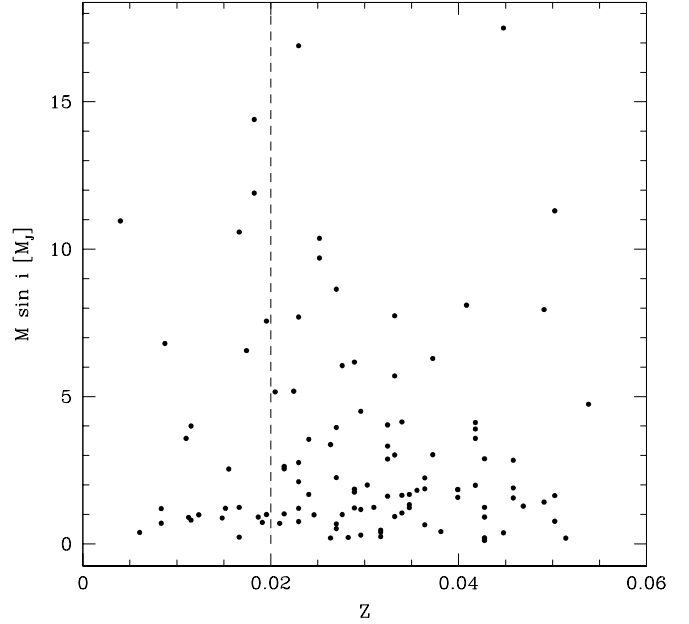


FIG. 3.— Same as Fig. 1, but for mass function  $M \sin i$  vs. metallicity  $Z$ .

This work was supported by grant AST 02-01266 from the NSF.

#### REFERENCES

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